

RESEARCH ARTICLE

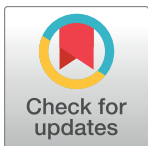
The Parametric Study and Fine-Tuning of Bow-Tie Slot Antenna with Loaded Stub

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Abstract

A printed Bow-Tie slot antenna with loaded stub is proposed and the effects of changing the dimensions of the slot area, the stub and load sizes are considered in this paper. These parameters have a considerable effect on the antenna characteristics as well as its performance. An in-depth parametric study of these dimensions is presented. This paper proposes the necessary conditions for initial approximation of dimensions needed to design this antenna. In order to achieve the desired performance of the antenna fine tuning of all sizes of these parameters is required. The parametric studies used in this paper provide proper trends for initiation and tuning the design. A prototype of the antenna for 1.7GHz to 2.6GHz band is fabricated. Measurements conducted verify that the designed antenna has wideband characteristics with 50% bandwidth around the center frequency of 2.1GHz. Conducted measurements for reflection coefficient (S_{11}) and radiation pattern also validate our simulation results.

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Introduction

As can be understood from many published works, various multiple communication techniques play a major role to improve the reliability and performance of the contemporary communication system. One of the techniques to support the increasing demand for the long range data communication is using the long-haul fiber-optic communication systems [1] and wavelength-division multiplexed systems [2]. Another invented multiple communication techniques as an interesting major of new researches for next generation communication systems are multiple-antenna systems and multiuser communications [3].

Recent and growing developments in wireless communication systems require wideband, low profile, small size, lightweight and low-cost antennas [4–9]. Low profile patch antennas such as microstrip and printed slot antenna meet these requirements. Nevertheless, a well-known drawback of the patch antenna is its intrinsic narrow bandwidth. Although different shapes of printed monopole antennas such as meander shaped [10], modified square-shaped [11], inverted double L-shaped [12], modified Inverted-L shaped [13], twin stepped patch [14], double-T shaped [15] and arc-shaped [16] are employed, they cannot provide a large enough bandwidth to cover wideband applications.

Rapid developments of wireless communication technologies generally require two-way data communication in a fast, high-efficiency and reliable way, which is reflected in the antenna subsystem [17]. A dual band H-slot microstrip patch antenna is presented to cover two frequency bands of 3.6–3.7 GHz and 5.7–5.8 GHz [17]. Another published work presented a low-profile, single layered rectangular microstrip antenna for 2.45 GHz and 4.96 GHz bands [18]. Although some of designs may provide dual or multi-band operations, the bandwidth around each resonant frequency is not large enough. Therefore, there are a variety of techniques to be applied and increase the bandwidth of the antenna. A slotted antenna is one of the effective candidates for exhibiting wideband characteristics by the printed antenna [19–23]. Desired bandwidth can be achieved by tuning the input impedance of the antenna by means of varying slot dimensions or geometry [24], using different patch shapes or using notched ground plane. The latter creates a capacitive load that compensates the natural inductive load of the monopole and makes the input impedance nearly-resistive [19]. A novel design presented a probe feed miniaturized dual-band microstrip antenna fabricated on a single layer patch. It used an asymmetric J Slot to achieve its desired characteristics [25].

One of the wideband antenna geometries is the Bow-Tie antenna that can be fed by coaxial line [26, 27], coplanar waveguide [28, 29] and stripline [30]. It has the advantages of low profile antennas with wideband characteristics and high radiation efficiency. The Bow-Tie antenna has been used in many applications such as WiFi [31] ground penetrating radars (GPR) [32–34] and pulse antennas [26, 27, 35]. Literature review for the Bow-Tie slot antennas demonstrates the wideband characteristics of this structure [29, 36–40].

The simple structure as well as the performance of the antenna are important issues in the design. The simple-structure wideband antenna has been realized by both microstrip line feeding structure and coplanar waveguide (CPW) feeding structure [19]. The antenna for this purpose should provide an easy means of fabrication and installation to facilitate parallel and series connections with circuit elements (for matching and gain enhancement) and easy integration with Monolithic Microwave Integrated Circuits (MMICs) [41, 42]. CPW-fed printed slot antenna provides easy means of integration with MMICs [43] in addition to its advantages for demonstrating the wider bandwidth as well as less radiation loss and less dispersion [19, 29].

There are some publications that they mainly has studies the characteristics of dual- or multi-band microstrip antennas and experimentally described how satisfying are their performance [17]. In this paper, a printed Bow-Tie slot antenna fed by a coplanar waveguide and directly matched to the 50Ω SMA connector for wide bandwidth applications has been presented and discussed. The antenna is carefully analyzed to determine the effects of all dimensions on the reflection coefficients in the working frequency band. The analysis and assessment of the antenna is performed by the CST Microwave Studio™. This computer simulation software package employs the Finite Integration Technique for electromagnetic computation. Simulation results provide a good initial approximation of antenna dimensions and suggest proper tuning trends to achieve desired performance. The radiation patterns of the antenna in E and H planes are presented. The antenna prototype is built by generic printed circuit board (PCB) technologies, and measurement results prove the validity of our simulations.

Antenna Design

Coplanar waveguide (CPW) feeding with loaded stub used for the antenna and some modifications have been applied to the geometry to comply with our desired performance and characteristics. The proposed geometry is shown in Fig 1. The parametric design of the antenna provides more degrees of freedom for tuning purposes during simulation and parametric

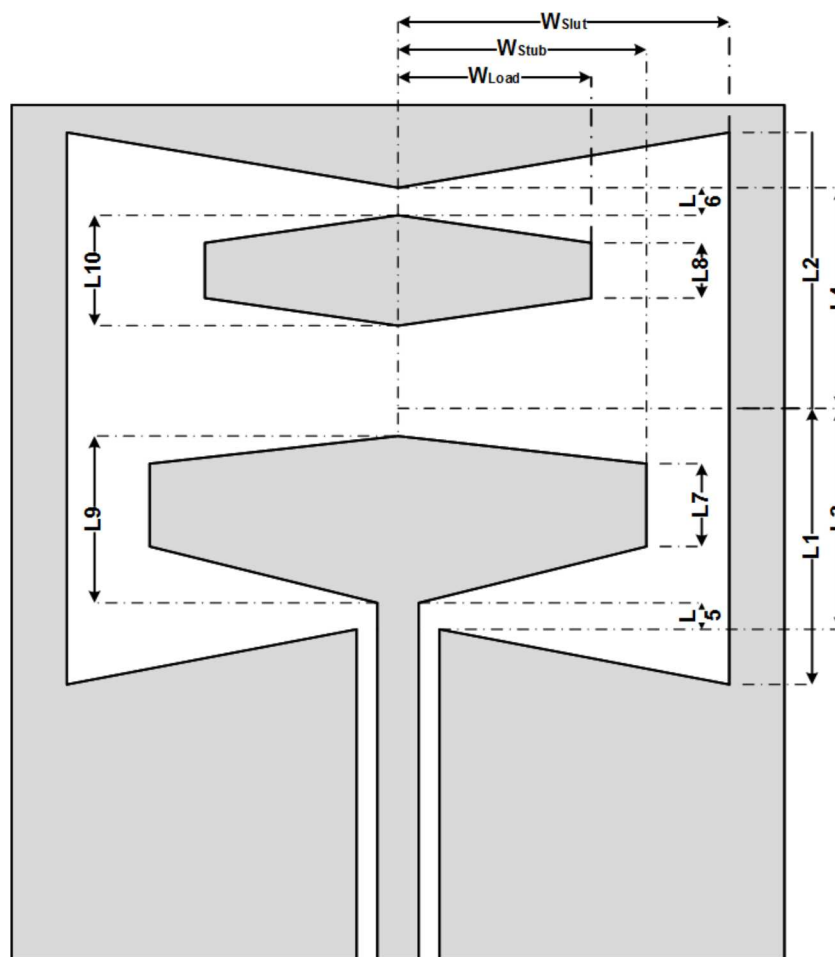


Fig 1. Geometry of the Proposed Bow-Tie Antenna.

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study during the analysis. The width and length of the Bow-Tie slot next to the tuning of the stub and load define the effective parameters. These sizes must be taken into account for a full analysis of the antenna.

The dimensions of the antenna are presented by variables such as, width of the slot (W_{Slot}), width of the stub (W_{Stub}), width of the load (W_{Load}), length of the slot (L_{Slot}), aperture of the slot (A_{Slot}), length of the stub (L_{Stub}), aperture of the stub (A_{Stub}), length of the load (L_{Load}), aperture of the load (A_{Load}), length of the first gap (L_{G1}) and length of the second gap (L_{G2}). These variables determine the size and geometry of the proposed antenna. The sizes used for our fabrication are: (All sizes are in millimeter)

$$\begin{aligned} W_{Slot} &= 44 & L_{Slot} &= 32 & L_{Stub} &= 4 & L_{Load} &= 3 \\ W_{Stub} &= 32 & A_{Slot} &= 21 & A_{Stub} &= 8 & A_{Load} &= 7 \\ W_{Load} &= 20 & L_{G1} \text{ \& } L_{G2} &= 0.5 \\ W_{substrate} &= 55 & L_{substrate} &= 54 \end{aligned}$$

In this design W_{Slot} is the Bow-Tie slot width. The changes of W_{Slot} presents changes in the width of the slot area. Also L_{Slot} is the Bow-Tie length and the changing of L_{Slot} presents

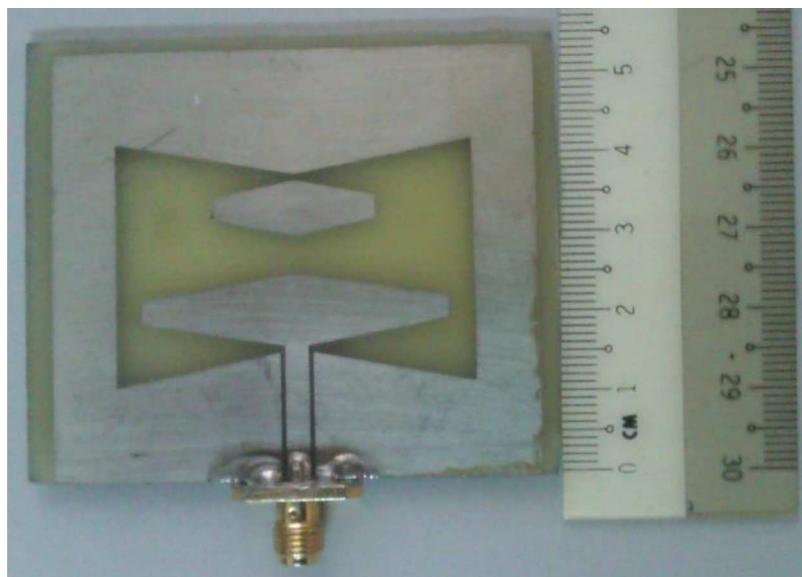


Fig 2. Fabricated Antenna.

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changes in the length of the slot area. The A_{Slot} determines the indent size of the Bow-Tie and shows the inner aperture of the slot.

The stub and the load are located inside the patch area. The W_{Stub} presents the width of the stub embedded inside the Bow-Tie slot area and width of the load object is presented by W_{Load} . The other parameters like L_{Stub} , A_{Stub} , L_{Load} and A_{Load} present the length and aperture of the stub and load in the middle and on the edge.

Fig 2 presents the fabricated antenna. The proposed antenna has only one side fabrication which makes the antenna easier for fabrication and integration. For the fabrication board we used copper coated FR4 material. The relative permittivity (ϵ_r) of the fiber is 4.3 and it has 1.6mm thickness.

In this paper, the effect of the width, length and indent of the slot area has been studied and analyzed as well as the width and aperture of the stub and the load. These analyses provides a clear indication of the influences of each parameter on the characteristics and reflection coefficient (S_{11}) or return loss of the antenna. This information can facilitate the final design to comply with our requirements and in tuning the antenna for other purposes.

Simulation and Measurement Results

Fig 3 presents S_{11} for the designed antenna in both simulation and measurement. It presents the reflection coefficient of the feed port and express the amount of return loss that occurs due to the port mismatch. As long as the S_{11} is lower than -10dB line, the return loss is acceptable and the antenna is considered to deliver a large enough portion of the power to the environment.

Although the measurement presents lower bandwidth than the simulation results, nevertheless the antenna covers the desired 1.7GHz to 2.6GHz frequency band. The difference between simulation and measurements occurred due to the imperfect situation during the measurement. There are many parameters directly influencing the return loss such as the losses that occur because of the SMA connector and the real amount of the relative permittivity of the substrate. As presented in the figure, if the amount of below -8.5dB are considered to be

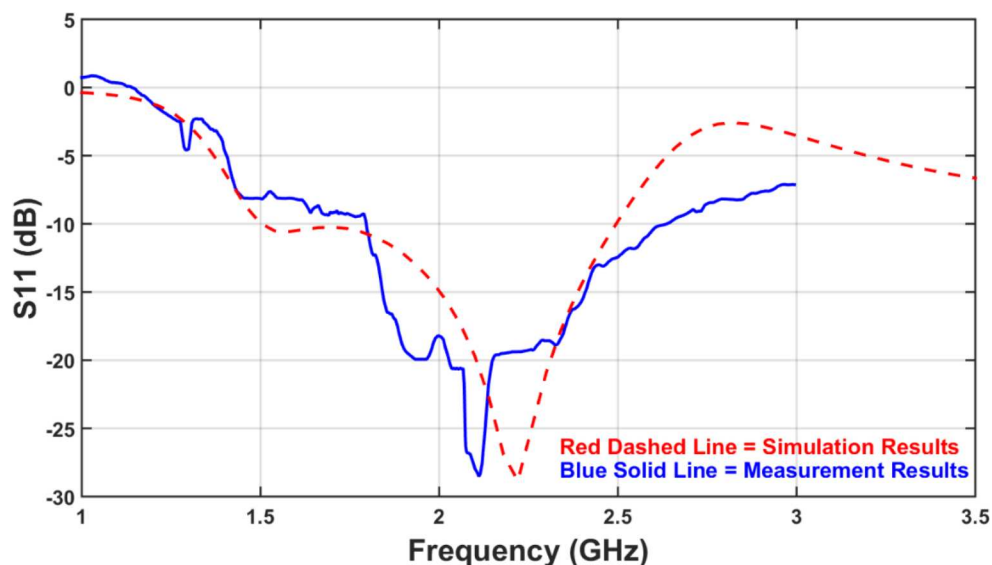


Fig 3. Reflection Coefficient (S_{11}): Simulation versus Measurement.

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the desired amount for S_{11} , the achieved bandwidth in simulation and measurement shows no significant difference. Therefore the losses in practice are higher than simulation.

The characteristics of this antenna will be changed by changing the dimensions of the designed geometry. One of the most important characteristics of the antenna is return loss. As shown in the Fig 3, there are two resonant frequencies. If they are near enough to each other and have lower return loss, wide bandwidth property is reachable by the antenna. So the effect of antenna dimensions must be explained for both lower and higher resonant frequencies (F_L and F_H respectively). The characteristics of the design can be tuned by changes applied to the slot as well as the stub and load embedded in the slot geometry.

The reflection coefficient can express voltage standing wave ratio (VSWR). The simulation and measurement results for the VSWR are demonstrated in Fig 4. It describes the power reflected from the antenna input port.

$$VSWR = \frac{1 + |S_{11}|}{1 - |S_{11}|}$$

Effects of Slot Dimensions

Fig 5 presents the reflection coefficient (S_{11}) of the antenna port for different sizes of W_{slot} . According to the presented graph, it is immediately obvious when the amount of W_{slot} size increases, the F_L decreases a great deal and the F_H changes slightly. This potentially indicates that by increasing the width of the slot, the bandwidth will increase.

Another effect is in the middle of S_{11} graph and it can be seen for a larger width of the slot, the peak between F_L and F_H becomes closer to -10dB and may pass this line and become higher than -10dB. Consequently, increment of the slot width in antenna geometry can cause a band-stop between F_L and F_H . Effects of changing in slot width on lower resonant frequency are more significant than effects on higher resonant frequency.

Fig 6 shows the effect of the L_{slot} changes on the reflection coefficient. L_{slot} is the Bow-Tie slot length and when it increases, both F_L and F_H decrease. The changing of F_H has been

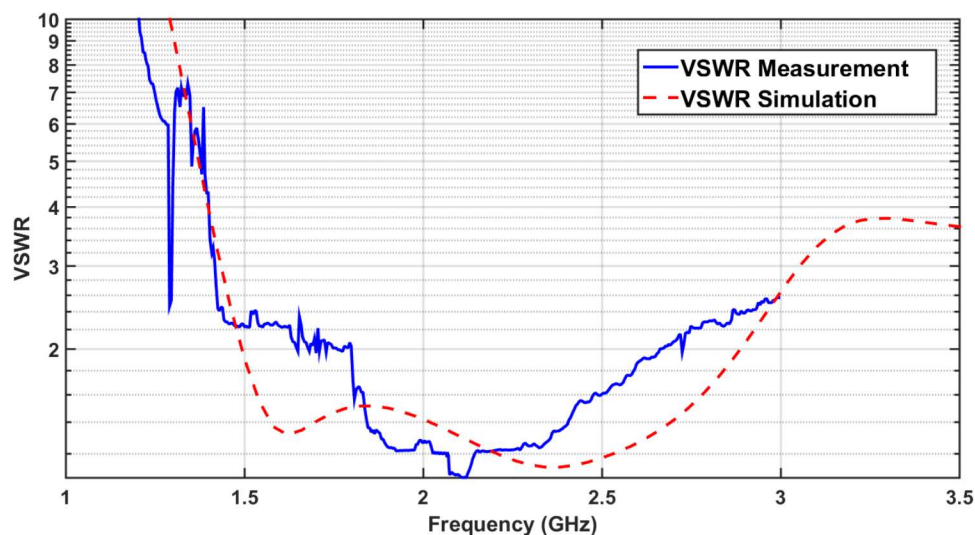


Fig 4. Voltage Standing Wave Ratio (VSWR): Simulation versus Measurement.

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significant while changing of F_L has been minimal. Consequently, by increasing the slot length, the bandwidth of the antenna remains almost constant or decreases slightly. By means of the slot length, we can control the working frequency band of the antenna. This can be shifted to the higher or lower bands by decreasing and increasing slot length respectively. The total bandwidth of the antenna will not change significantly.

On the other hand, when slot length increases, return loss at F_L moves closer to the -10dB line. The return loss changes at F_H are contradictory. Therefore, increasing of the slot length

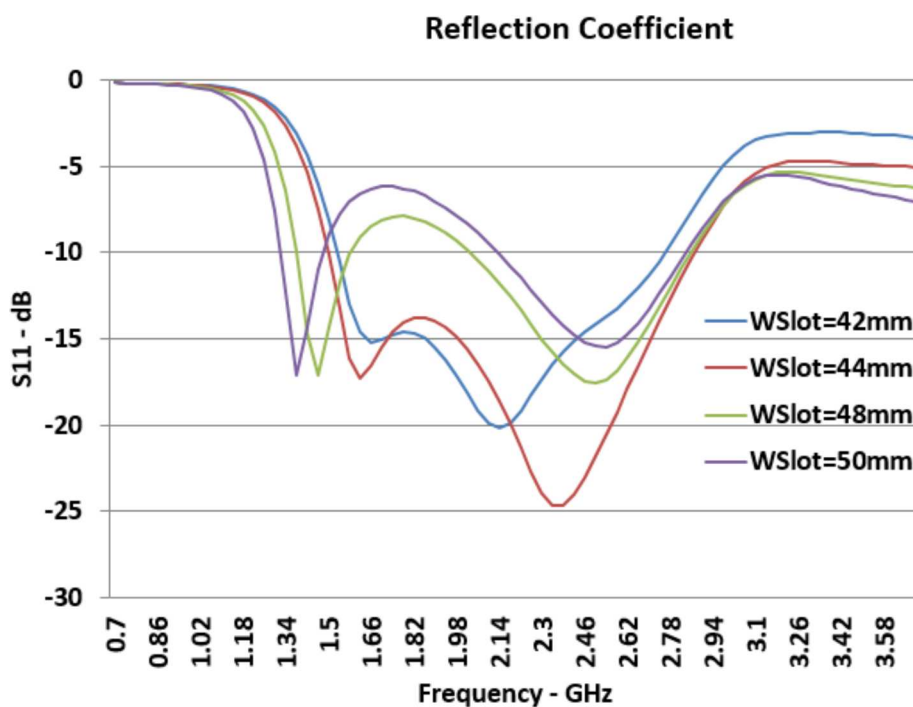


Fig 5. Effect of W_{Slot} Changes on Reflection Coefficient (S_{11}).

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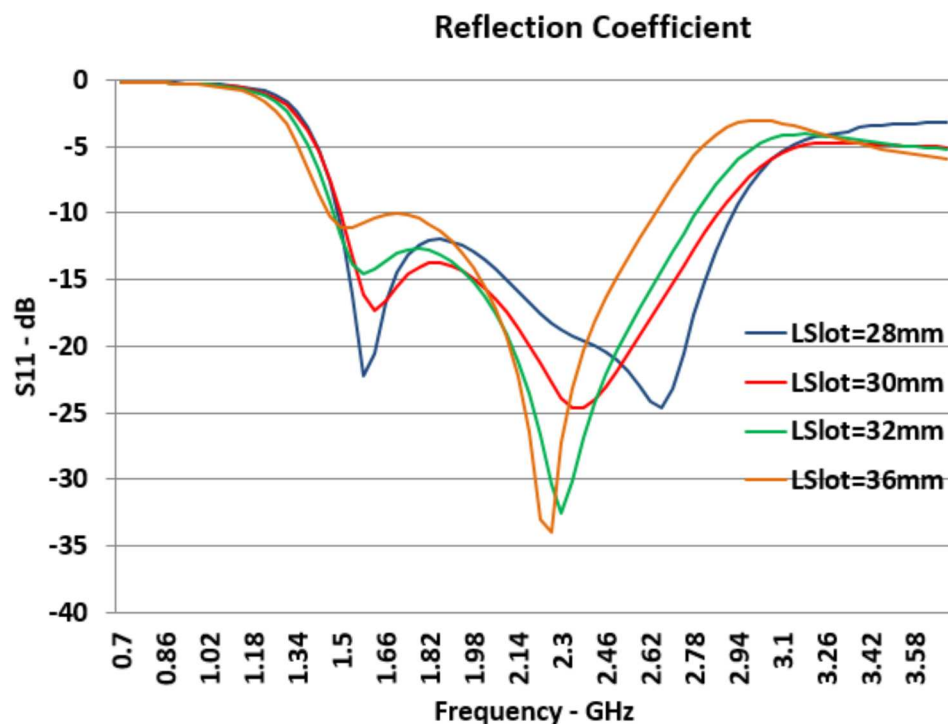


Fig 6. Effect of L_{Slot} Changes on Reflection Coefficient (S_{11}).

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causes more reflection at the feed port for the lower resonant frequency while it makes lower reflection at higher resonant frequency.

Effects of the Stub Dimensions

Stub dimension significantly affects the performance and characteristics of the designed antenna. The stub has two apertures (inside and outside) and a width all of which require study.

W_{Stub} is the width of the stub which is located inside the Bow-Tie slot area. Graphs presented in Fig 7 shows the increment of stub width has no significant effect on F_L while it moves F_H to lower frequencies significantly; thus, by increasing the width of the stub, potentially the bandwidth potentially becomes smaller and obviously the center frequency shifts to the lower range.

As it can be seen in Fig 7, by means of increasing the stub width, the reflection coefficient at lower resonant frequency (F_L) becomes smaller while it has the inverse effect at the higher resonant frequency.

L_{Stub} presents the size of the outer aperture of the stub. Fig 8 presents the effect of changes in the size of this aperture on the return loss of the designed antenna. When the outer aperture of the stub component increases, F_H became smaller and F_L becomes larger; consequently, the bandwidth has been reduced. Increasing the size of the outer aperture has contradictory effects on the return loss at F_L and F_H . Although the increasing of L_{Stub} has little effect on the S_{11} at lower resonant frequency and makes the reflection coefficient closer to the -10dB line, it has a significant effect in the reverse direction on S_{11} at the lower resonant frequency.

The effect of changing in A_{Stub} size has been presented in the graphs of Fig 9. It is immediately obvious that these changes do not have a significant effect on higher and lower resonant frequencies but they have effects on return loss at both higher and lower resonance frequencies. Increasing inner aperture size causes lower S_{11} at higher resonant frequency while it makes a

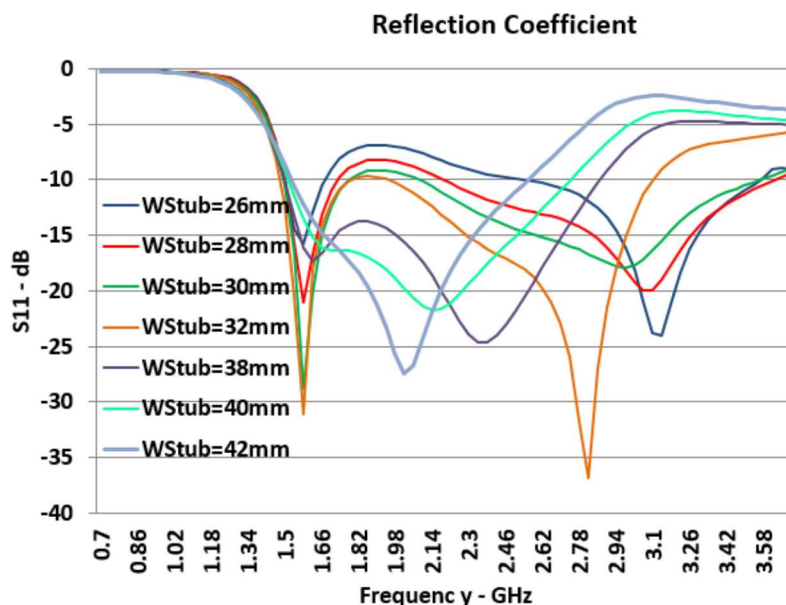


Fig 7. Effect of W_{Stub} Changes on Reflection Coefficient (S_{11}).

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contradictory effect at lower resonant frequency. If the size of A_{Stub} becomes larger than what is presented, it can provide a band stop in the middle of the antenna bandwidth. So A_{Stub} can be used to tune the reflection coefficient in both F_L and F_H and also provide a band stop.

Effects of the Load Element Dimensions

W_{Load} is the width of the load component which is located on top of the stub. W_{Load} determines the total width of the load and it can be used as a tuning component. By increasing the

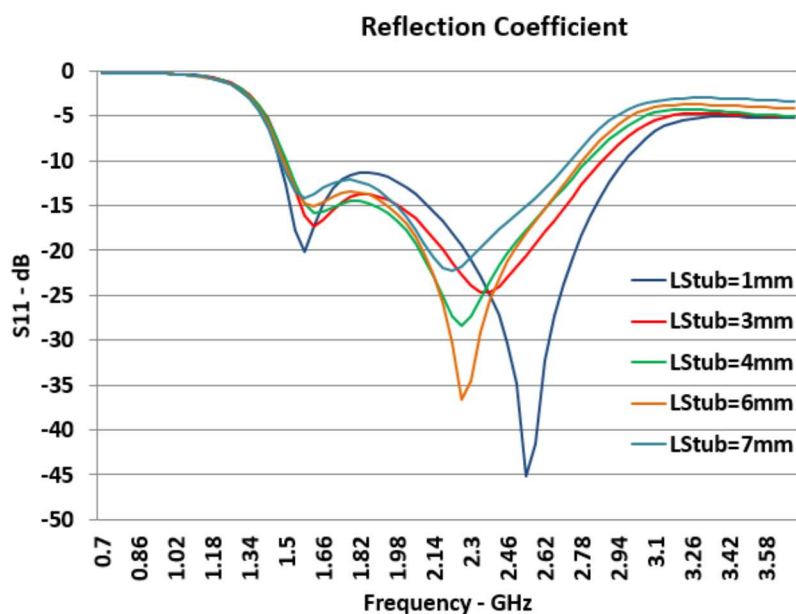


Fig 8. Effect of L_{Stub} Changes on Reflection Coefficient (S_{11}).

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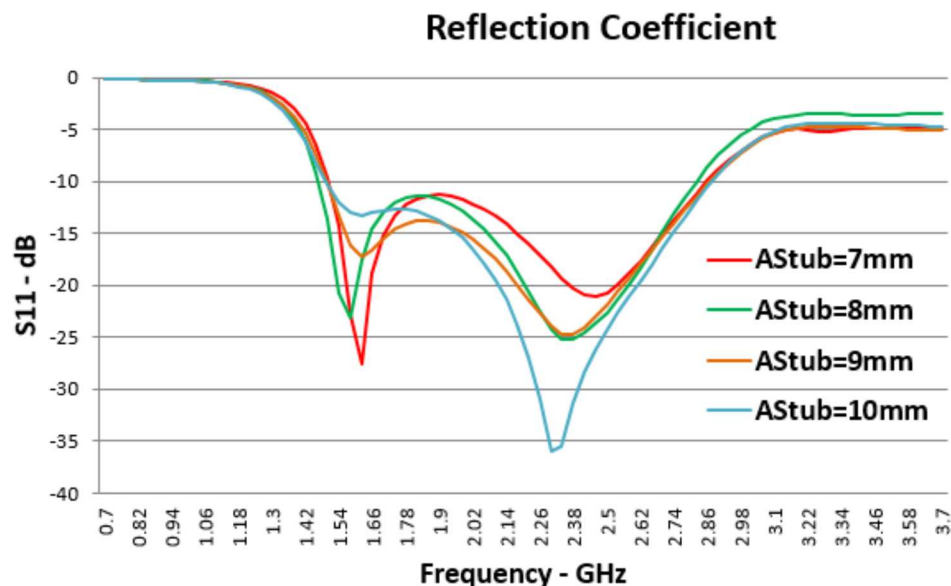


Fig 9. Effects of A_{Stub} Changes on Reflection Coefficient (S_{11}).

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W_{Load} , F_H reduces slightly and there is no significant change in F_L . The return loss at F_H decreases while W_{Load} became larger. So the width of this tuning load can be used for controlling the reflection coefficient of the higher resonant frequency with no significant change in the bandwidth. This is concluded from the graphs presented in Fig 10.

The graphs presented in Fig 11 shows the reflection coefficient for different sizes of the L_{Load} . L_{Load} presents the outer aperture of the load. Increasing the L_{Load} provides slight changes at both higher and lower resonance frequencies and they are contradictory. If the outer aperture size increases, F_L shifts right slightly and F_H shifts a bit left. Consequently, the working

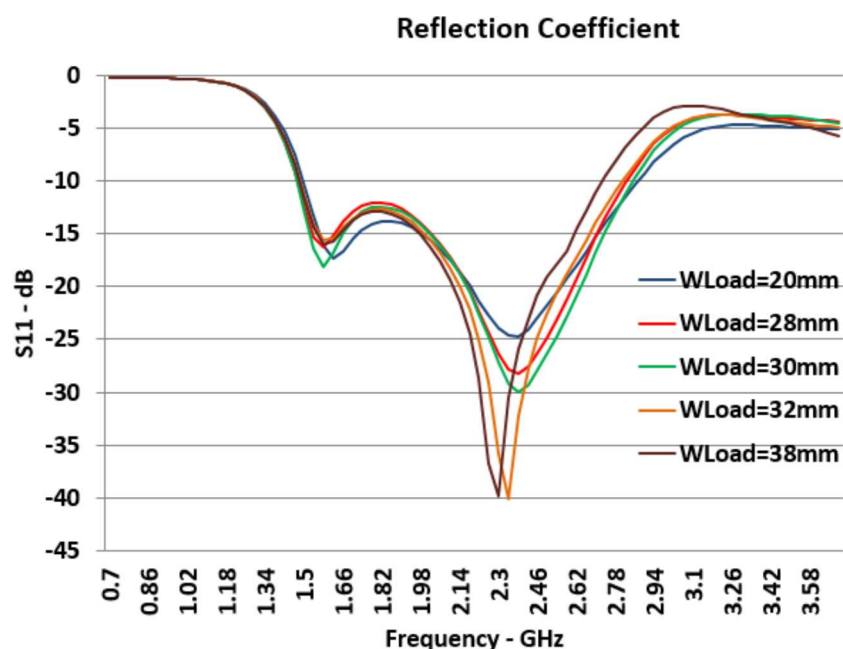


Fig 10. Effects of W_{Load} Changes on Reflection Coefficient (S_{11}).

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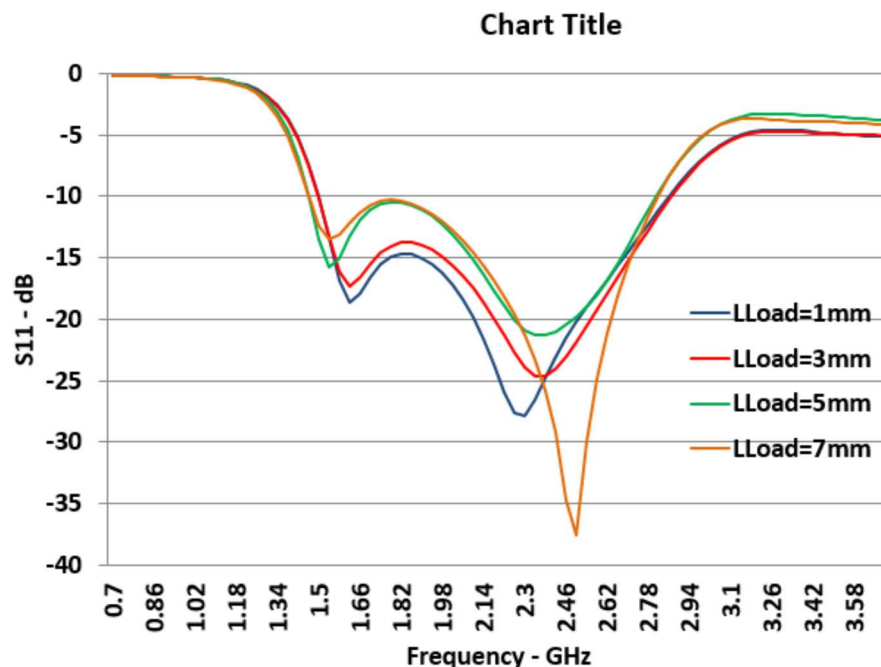


Fig 11. Effects of L_{Load} Changes on Reflection Coefficient (S_{11}).

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bandwidth of the designed antenna becomes a bit smaller. The reflection coefficient graph at both higher and lower resonant frequencies moves higher. So, this parameter of the antenna can be utilized to create a band stop in the middle of the bandwidth which may be used for some applications to prevent interferences.

A_{Load} determines the inner aperture of the load component. Graphs presented in Fig 12 show that this aperture can be used to control the return loss of the antenna in its working

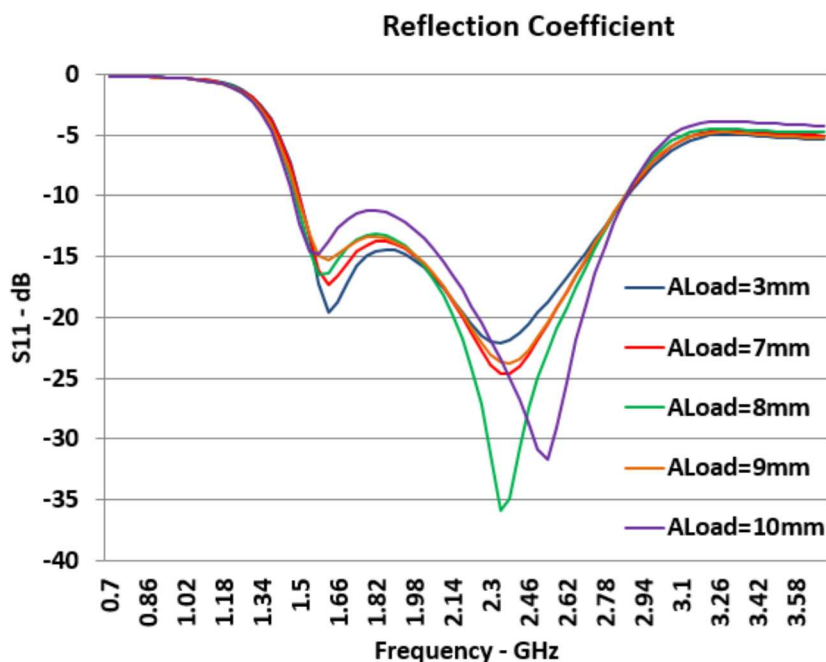


Fig 12. Effects of A_{Load} Changes on Reflection Coefficient (S_{11}).

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bandwidth. As observed from graphs, when A_{Load} increases, S_{11} at lower resonance frequency moves closer to $-10dB$ line and moves higher.

Radiation Pattern

The radiation patterns of the fabricated antenna have been measured in an anechoic chamber in two principal planes: E-Plane and H-Plane. The results are normalized to the maximum value of the resonant frequency and they are shown in Fig 13 and Fig 14. The solid line and the dashed line are co-polarized and cross-polarized components, respectively.

It can be observed that the antenna exhibits approximately omni-directional radiation patterns for H-plane. Because the wavelength is much larger than the antenna size at working frequency, the radiation pattern in E-plane is nearly symmetrical. Although the electrical length increases with higher frequencies, the evident asymmetry in the radiation pattern occurs because of the CPW feeding structure. This effect becomes smaller at higher resonant frequency. When the frequency increases, higher order harmonic introduces to patterns and patterns become more directional but still remain almost omni-directional. The measured radiation patterns of the antenna are similar to those of a typical monopole antenna.

Analysis

The antenna consists of three major components: slot area, stub and load. The dimensions of these components enforce changes in antenna characteristics and its performance effectively. Any optimum design of the antenna needs a correct and in-range initial approximation. According to the parametric studies of the antenna, initial values for the size of each part are proposed as presented in Table 1.

As it can be seen in the Table 1, slot area size is proportional to the wavelength and its dimension interval limited between two amounts that are a fraction of the wavelength. The width of the slot area of the antenna can be at least a quarter of the wavelength and at most $3\lambda/8$. The length of the slot area could be between an octant of the wavelength to a quarter of the wavelength.

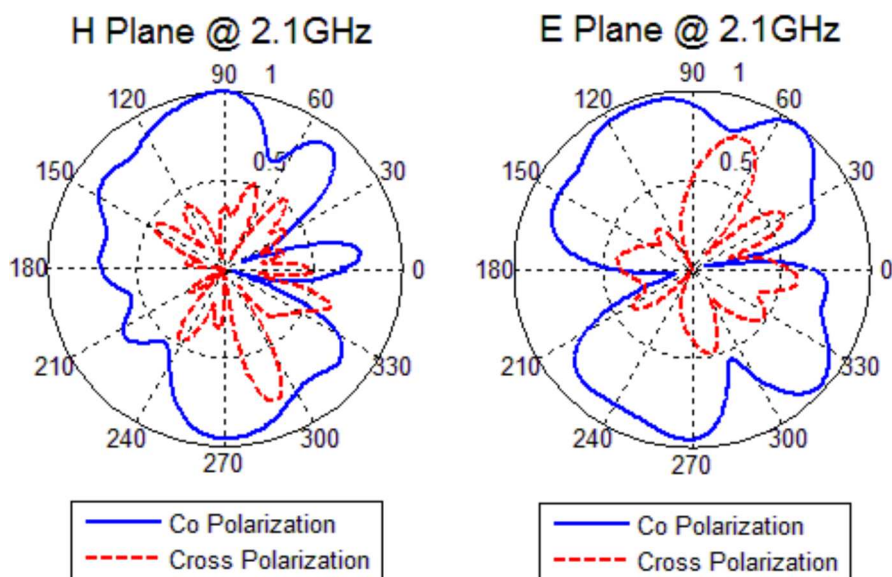


Fig 13. Measured Radiation Patterns at 2.1 GHz.

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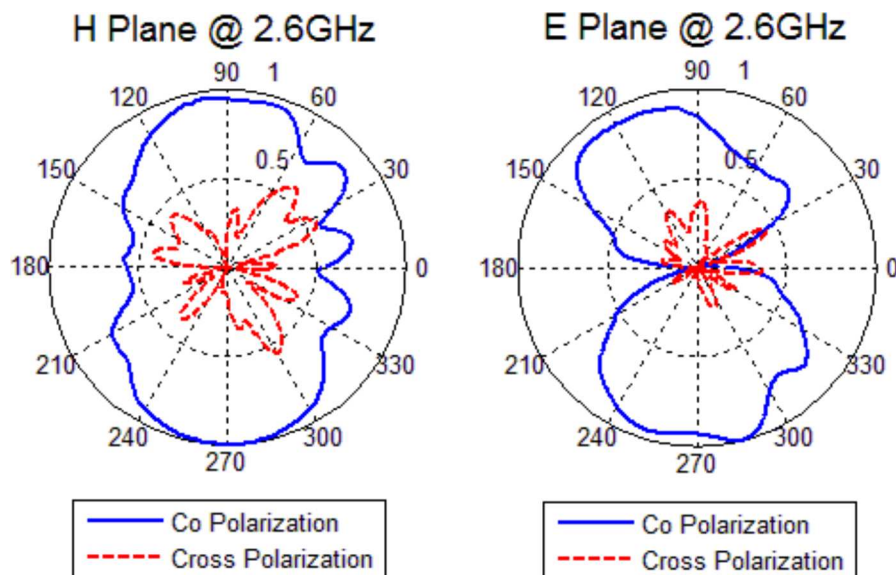


Fig 14. Measured Radiation Patterns at 2.6 GHz.

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As shown, the width of the stub and the load are proportional to the wavelength as well. Nevertheless, aperture size of the stub and the load is a percentage of the slot length. In addition, it is necessary for the apertures not to exceed $\lambda/8$.

Table 1 can be used for the approximation of the dimensions. These approximations can be used as a starting point for the antenna design to reach the desired frequency band. These approximated dimensions achieve a frequency band which is near to our desired band and they are not the exact size of the antenna. After that, the dimensions must be tuned to get better performance and achieve the exact frequency band for our purposes. Indeed, conditions mentioned in Table 1 are necessary, but are not sufficient. As was elaborated in previous sections, regarding the changes in the dimensions of the slot, stub and load, the final tuning can be accomplished by means of our proposed parametric studies for tuning purposes shown in Table 2.

Table 1. Initial Design Approximations.

Component		Min Value	Max Value
Slot	Width	$\lambda/4$	$3\lambda/8$
	Length	$\lambda/8$	$\lambda/4$
Stub	Width	$\lambda/8$	$3\lambda/8$
	Outer Aperture	3% of SL*	25% of SL
	Inner Aperture	20% of SL	33% of SL
Load	Width	$\lambda/8$	$\lambda/4$
	Outer Aperture	3% of SL	25% of SL
	Inner Aperture	10% of SL	33% of SL

* SL: Total Slot Length.

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Table 2. Effects of size increment on FL, FH and S11.

Effect of Increasing		FL	S11@FL	FH	S11@FH
Slot	W_{Slot}	←	—	—	—
	L_{Slot}	←	↑	←	↓
Stub	W_{Stub}	—	↓	←	↑
	L_{Stub}	→	↑	←	↓
	A_{Stub}	—	↑	—	↓
Load	W_{Load}	—	—	←	↓
	L_{Load}	→	↑	←	↑
	A_{Load}	—	↑	—	—

←: Frequency shifts lower.

↑: S11 graph moves higher.

→: Frequency shifts higher.

↓: S11 graph moves lower.

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Conclusion

This paper proposed a CPW-Fed printed Bow-Tie slot antenna with loaded stub. Effects of changing in the sizes of slot, stub and load dimensions are considered and then a solution is suggested for design purposes. For any antenna design, the designer needs to know the dimension ranges to consider the limitations of the design. The dimension ranges could be determined by means of some initial values at first and then the final design and final values of the dimensions could be achieved by optimizing those initial values. This paper proposed a reasonable initial approximation for the first design (Table 1). A second table is used for fine-tuning for the final design (Table 2). The designed antenna has wideband characteristics and it achieved more than 50% bandwidth around a centre frequency of 2.1 GHz.

CPW-Fed structure provides wider bandwidth with lower dispersion in comparison with Probe-Fed antennas. This characteristic is desired for many applications. Unipolar configuration of the single sided CPW-Fed antenna makes it easy to be implemented during fabrication and to integrate during utilization. This kind of printed antenna complies with the requirements of small size and light weight, so it is very useful for portable systems. Bow-Tie geometry provides radiation characteristics similar to rectangle antenna, but with smaller size. There are loaded stub which is useful for tuning.

The characteristics of the proposed antenna change by hanging in the dimensions of the designed geometry. The proposed antenna achieved our desired bandwidth. As indicated, it can be tunable with loaded stub that are embedded in the slot geometry. The results are proven through simulation, fabrication and measurement.

Supporting Information

S1 Table. This is the Initial Design Approximations.
(DOCX)

S2 Table. This is the Effects of size increment on FL, FH and S11.
(DOCX)

S1 Text. This is the results due to changes of L1.
(TXT)

S2 Text. This is the results due to changes of L5.
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S3 Text. This is the results due to changes of L7.
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S4 Text. This is the results due to changes of L8.
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S5 Text. This is the results due to changes of L9.
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S6 Text. This is the results due to changes of L10.
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S7 Text. This is the results due to changes of Wslot.
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S8 Text. This is the results due to changes of Wstub.
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S9 Text. This is the results due to changes of Wload.
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S10 Text. This is the S11 at final measurement.
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S11 Text. This is the radiation pattern measurement at final measurement.
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S12 Text. This is the reference file to plot Radiation Pattern.
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Data curation: MMS MM WNLWM.

Formal analysis: MMS MM WNLWM.

Funding acquisition: MMS MM WNLWM.

Investigation: MMS MM WNLWM.

Methodology: MMS MM WNLWM.

Project administration: MMS MM WNLWM.

Resources: MMS MM WNLWM.

Software: MMS MM WNLWM.

Supervision: MMS MM WNLWM.

Validation: MMS MM WNLWM.

Visualization: MMS MM WNLWM.

Writing – original draft: MMS MM WNLWM.

Writing – review & editing: MMS MM WNLWM.

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